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NASA Technical Memorandum 102630

MINI-MAST CSI TESTBED USER'S GUIDE

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January 1992

National Aeronautics and
Space Administration

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Introduction

Mini-Mast is a 20-meter-long generic space truss. The entire structure is readily accessible for various static and dynamic experiments. Mini-Mast was built primarily for research in the areas of structural analysis and testing. At the time of its construction in 1986, the design duplicated (except in length) the 60-meter-long truss developed under a flight experiment called MAST, hence the name "Mini-Mast." Manufactured by Astro Aerospace Corporation using flight-quality materials and workmanship[1], it is highly representative of future deployable trusses for space applications.

Mini-Mast has been used as the first ground testbed at NASA Langley Research Center (LaRC) for the Controls-Structures Interaction (CSI) program.[6] The objective of the facility is to conduct comprehensive active-vibration-control experiments on a dynamically realistic large space structure. A primary goal is to understand the practical effects of simplifying theoretical assumptions.

To support these experiments, actuators, sensors, and computer hardware have been added to the truss. Digital control algorithms are implemented on real-time computers, using vibration signals from the sensors to generate motion-suppressing forces with the actuators. Two stiff platforms at the tip and near the mid-point of the truss are used for mounting actuators and sensors for control. The signals are linked via fiber-optic cables to a mainframe CDC real-time computer system located in the LaRC Central Scientific Computing Facility. This computer system--the Advanced Real-Time Simulation (ARTS) system--is a fully-supported institutional resource.[2] The configuration of the testbed for CSI experiments was to have remained constant throughout the two-year CSI Guest Investigator Program; however, equipment failures with the rate gyro sensors necessitated changing the number of rate sensors available from five to three and finally to only one.

This document was initially released in preliminary format in March 1989 to provide Mini-Mast testbed users with an overview of the facility and its principal components. It is now being released in its present form to aid users in referencing information about the testbed set-up, operating procedures, and hardware. Other formal reports documenting specific aspects of the testbed have been released and are listed among the reference list at the end of this User's Guide.

Testbed Description

This section details information on the deployable-retractable truss, the off-loading cable, the equipment platforms, and the various sensors and torque wheel actuators. Computer hardware is discussed in the subsequent section on control law implementation.

The Mini-Mast Truss

Mini-Mast is a deployable/retractable generic space truss designed and manufactured by Astro Aerospace Corp., Carpinteria, CA. The truss is located in the Structural Dynamics Research Laboratory (Bldg. 1293B) at NASA LaRC. It is deployed vertically inside a high-bay tower, cantilevered from its base on a rigid foundation. Figure 1 shows an artist's conception of Mini-Mast superimposed in its correct orientation on a photograph on the high-bay tower.

The truss beam, sometimes referred to as an "Articulating Astromast," has three member types: longerons, battens, and diagonals. Longerons are parallel to the beam axis and provide beam stiffness and strength in bending. The three-longeron construction forms a triangular cross-section with points inscribed by a circle of diameter 1.4 meters (55 in). Battens are in the beam face planes, provide beam stability, and form the sides of the equilateral triangular cross-section. Finally, diagonals, also in the beam face planes, provide beam stiffness and strength in torsion and shear.

The truss is 20.16 meters (66.14 ft) long, containing 18 bays in a single-laced configuration with every other bay repeating. Figure 2 shows the preliminary deployment of the first two bays of the truss, while Figure 3 shows Mini-Mast anchored to the heavy base platform first in the stowed (retracted) position and then during initial deployment within the high-bay tower. Perspective views of the fully deployed truss in the high-bay tower are provided in Figure 4.

The original requirement for deployability created complicated structural components. Each of the 54 diagonals folds inward by means of a mid-span titanium hinge, allowing deployment or retraction of the truss. Figure 5 shows detailed views of the mid-diagonal hinges, in both the closed (locked) position and an intermediate position. Another type of complicated component is the corner-body joint. The 57 corner-body joints are made of machined titanium (6A1-4V annealed), using off-axis stainless steel pins for hinged connections for the longeron and diagonal members in order to allow rotation during deployment. Batten members are not hinged. Figure 6 shows a close-up view of a corner-body joint. The circular disk in the picture is a metal target, mounted to the corner-body joint, to serve as a target for the noncontacting displacement sensors, discussed later in this users' guide. Also visible in the picture is the stinger and load cell from on of the three shakers used to excite the structure. At bay 1 of the truss, the lowest three joints of the vertically cantilevered beam are bolted to ground.

All tubing members are made of graphite/epoxy, with the following geometric characteristics:

Table 1
Geometric Characteristics

MEMBER	LENGTH	OD	ID
Longerons	1.0920 m (42.99 in)	20.2 mm (0.795 in)	14.9 mm (0.587 in)
Battens	1.2124 m (47.73 in)	15.1 mm (0.594 in)	11.9 mm (0.469 in)
Diagonals	1.6225 m (63.88 in)	15.1 mm (0.594 in)	11.2 mm (0.441 in)

The Modulus of Elasticity of the tubes is nearly equal that of the titanium joints as follows:

Table 2
Material Properties

Component	Young's Modulus (E)
Tubes	1.24×10^{11} N/m (17.98×10^{6} lb/in)
Joints	1.13×10^{11} N/m (16.38×10^{6} lb/in)

A complete discussion of the design and manufacture of the structure, including additional information on its structural properties, is available in Ref. 1.

The truss members themselves are lightweight in comparison to other testbed hardware. The mass of the corner-body joints is more than 200 per cent of the mass of the truss, while the mid-diagonal hinges are 150 per cent more massive than the truss members. Even more significant, the fully loaded tip platform is more than 700 per cent more massive than the combined truss elements supporting it, which led to the installation of a tensioned cable to off-load the tip-plate mass. (Table 3 shows mass comparisons of the various testbed components.)

Cable Off-Loading Mechanism

A cable, attached to the geometric center of the Mini-Mast tip plate, serves to off-load the weight of the fully equipped tip platform (approximately 158 Kg or 350 lbs.) in order to prolong the fatigue life of the system. A sketch of the cable system is shown in Figure 7. The tension in the vertical cable is verified through a calibrated load cell and can be adjusted manually with the turnbuckle. Temperature variation throughout the day affects the thermal expansion of the both the high-bay tower to which the cable is anchored and the cable itself. Five percent

Table 3

Mass Summary

Testbed Component	Mass
Truss members	20.895 kg
Corner body joints	44.318 kg
Corner targets for noncontacting displacement sensors	7.268 kg
Mid-diagonal hinges with associated hardware	31.789 kg
Tip plate (Bay 18)	40.444 kg
Torque wheel actuator X	38.703 kg
Torque wheel actuator Y	38.816 kg
Torque wheel actuator Z	33.022 kg
Bay 18 Accelerometers	0.515 kg
Bay 18 rate gyro	0.186 kg
Mid Plate (Bay 10)	12.587 kg
Bay 10 brackets (in corners)	0.234 kg
Bay 10 accelerometers	0.257 kg
Bay 10 rate gyros	0.270 kg
Bay 10 added lumped mass	36.288 kg
Total Mass	305.589 kg

variation in the cable load can occur due to temperature changes in a typical day; this level is considered acceptable for testing. During the summer months, turnbuckle adjustments are often required immediately before testing to stay within the $\pm$ 5 percent range.

Cable effects on the modal characteristics of the testbed are negligible except in the first bending modes, which increased slightly in frequency due to the small pendulum stiffness of the cable. With the addition of the cable to the testbed, frequency of the first bending mode rose from approximately 0.65 Hz to approximately 0.86 Hz . Swivel links included in the cable attachment minimize cable effects on torsion modes.

Actuators and Sensors

The baseline equipment configuration is illustrated in Figure 8. Three primary categories exist: equipment used for control purposes, equipment used for disturbance generation and measurement, and equipment used for post-test analyses. These categories, however, are not exclusive. For instance, while the torque wheel actuators on the tip plate are the only actuators available to guest investigators for control purposes, the same actuators can be used for excitation. In addition, while one could argue that the displacement sensors (which are attached to ground) are not representative of types of sensors that will be available in space and therefore would be best suited for post-test analyses, a researcher could still select them as feedback signals for control purposes. Note that only those displacement sensors from Bays 6, 10, 14, and 18 are linked to the controls computer.

Open-loop or closed-loop modal identification tests can be performed by guest investigators with the GenRad 2515 ITAS system. The ITAS system consists of a 16-channel GenRad 2515 Computer-Aided Test (CAT) system, interfaced with a high-speed parallel line to a MicroVax 3200 workstation. The GenRad is equipped with a 128-channel scanner that can access data in 16-channel groups under software control. It can be programmed to acquire time histories and/or frequency response functions automatically for all connected channels. It can be used to identify not only closed-loop natural frequencies and damping factors, but closed-loop mode shapes using the full complement of displacement sensors, as well. Bays 2 through 18 each have 3 displacements sensors, one at each vertex of the triangular cross-section of the truss.

Several photographs can help clarify the concepts and equipment discussed in this section. Figure 9 shows the torque wheel actuators and servo accelerometers mounted on the tip plate. Referring back to Figure 6, one can see the attachment of one of the bay 9 shakers used for modal testing and closed-loop disturbance. Figure 10 shows one of these sensors, a 50-mm (2-inch) Kaman displacement sensor.

Identification information for each of the actuators and sensors to be used in CSI experiments are contained in Table 4 (a) through (c). This information includes the joint location numbers (labeled "Grid") corresponding to the finite element model and the modal influence coefficients from each mode shape. In addition, the bay number and spacial coordinates of each device are also provided in the table. Concise abbreviations included for each instrument can be used to ensure accurate communication among researchers.

Table 4

Location of Mini-Mast Actuators and Sensors

Table 4 (a): Locations of Mini-Mast Actuators

Device	**Direction (Abbreviation)**	**Bay**	**Grid**	**X**	**Y**	**Z**
Torque Wheel Actuators	About X (TWA-X)	18	350	-0.590	0.419	20.509
	About Y (TWA-Y)	18	349	0.419	-0.610	20.509
	About Z (TWA-Z)	18	348	0.000	0.000	20.232
Shakers	@ Vertex A (S1)	9	166	0.0000	0.700	10.080
	@ Vertex B (S2)	9	167	0.6062	-0.350	10.080
	@ Vertex C (S3)	9	168	-0.6062	-0.350	10.080

Table 4(b): Locations of Recommended Control Sensors

Device	**Direction (Abbreviation)**	**Bay**	**Grid**	**X**	**Y**	**Z**
Accelerometers	X (A1)	18	342	-0.6258	0.6258	20.176
	Y (A2)	18	340	-0.6258	-0.6258	20.176
	X (A3)	18	338	0.6258	-0.6258	20.176
	Y (A4)	18	336	0.6258	0.6258	20.176
	X (A5)	10	355	0.2290	0.0000	1.200
	Y (A6)	10	355	0.2290	0.0000	11.200
Rate Gyros	X (R1)	18	345	-0.5588	-0.5588	20.176
	Y (R2)	18	345	-0.5588	-0.5588	20.176
	Z (R3)	18	345	-0.5588	-0.5588	20.176
	X (R4)	10	354	-0.2540	0.0000	11.200
	Y (R5)	10	353	0.0000	0.5460	1.200

Table 4(c): Displacement Sensor Locations

Position	Abbrev	Bay	Grid	Z
Vertex A	(D1)	2	40	2.24
Vertex B	(D2)	2	41	2.24
Vertex C	(D3)	2	42	2.24
Vertex A	(D4)	3	58	3.36
Vertex B	(D5)	3	59	3.36
Vertex C	(D6)	3	60	3.36
Vertex A	(D7)	4	76	4.48
Vertex B	(D8)	4	77	4.48
Vertex C	(D9)	4	78	4.48
Vertex A	(D10)	5	94	5.60
Vertex B	(D11)	5	95	5.60
Vertex C	(D12)	5	96	5.60
Vertex A	(D13)	6	112	6.72
Vertex B	(D14)	6	113	6.72
Vertex C	(D15)	6	114	6.72
Vertex A	(D16)	7	130	7.84
Vertex B	(D17)	7	131	7.84
Vertex C	(D18)	7	132	7.84
Vertex A	(D19)	8	148	8.96
Vertex B	(D20)	8	149	8.96
Vertex C	(D21)	8	150	8.96
Vertex A	(D22)	9	166	10.08
Vertex B	(D23)	9	167	10.08
Vertex C	(D24)	9	168	10.08
Vertex A	(D25)	10	184	11.20
Vertex B	(D26)	10	185	11.20
Vertex C	(D27)	10	186	11.20
Vertex A	(D28)	11	202	12.32
Vertex B	(D29)	11	203	12.32
Vertex C	(D30)	11	204	12.32
Vertex A	(D31)	12	220	13.44
Vertex B	(D32)	12	221	13.44
Vertex C	(D33)	12	222	13.44
Vertex A	(D34)	13	238	14.56
Vertex B	(D35)	13	239	14.56
Vertex C	(D36)	13	240	14.56
Vertex A	(D37)	14	256	15.68
Vertex B	(D38)	14	257	15.68
Vertex C	(D39)	14	258	15.68
Vertex A	(D40)	15	274	16.80
Vertex B	(D41)	15	275	16.80
Vertex C	(D42)	15	276	16.80
Vertex A	(D43)	16	292	17.92
Vertex B	(D44)	16	293	17.92
Vertex C	(D45)	16	294	17.92
Vertex A	(D46)	17	310	19.04
Vertex B	(D47)	17	311	19.04
Vertex C	(D48)	17	312	19.04
Vertex A	(D49)	18	328	20.16
Vertex B	(D50)	18	329	20.16
Vertex C	(D51)	18	330	20.16

Vertex	X-Position	Y-Position
A	0.0000	0.700
B	0.6062	-0.350
C	-0.6062	-0.350

Figure 11 shows schematically the placement of the instruments on the tip plate and mid plate, incorporating the abbreviations for identifications purposes. The grid surface represents the mounting plate. Some instruments measure response or impart torques in directions aligned with the global axes. However, the 3 shakers and 51 displacement sensors require additional coordinate transformations. Orientation of the shakers is illustrated in Figure 12, and displacement sensor orientations, which alternates for even and odd numbered bays, are shown in Figure 13.

All actuators and sensors recommended for use in control experiments are located on the platforms at Bays 10 and 18 and are denoted as control actuators and sensors in Table 5. The recommended use of the 51 displacement sensors distributed along the length of the truss is for observing structural response. The primary displacement sensors are distinguished from the secondary displacement sensors because only the former are linked to the real-time computer. This linkage would allow for their use as control feedback signal; such use, while not forbidden, is not recommended since measurements to ground are not applicable to on-orbit structures.

Three torque wheel actuators (TWAs) are mounted on the tip plate parallel to the global x, y, and z reference axes. The TWAs provide both torsional and bending torque loads to the Mini-Mast. The DC permanent-magnet motors have a rated peak output of 68 N-m (50 ft-lbs) at 50 volts and 9.6 amps. The motor torque constant is 7.061 N-m/amp (5.208 ft lb/amp) and its maximum speed is 66.8 RPM. The torque motor rotor is attached to an annular inertia wheel with an outer diameter of .61 m (24 in) and a total rotary inertia of 0.9491 N-m-sec (134.4 oz-in-sec). A frictional drive tachometer is attached to each wheel to provide rotor speed information. Weights for the X and Y axis TWAs and mounting frames are approximately 39 kg (85 lbs) each, while the weight for the Z axis TWA, with its smaller mounting frame, is approximately 33 kg (72.5 lbs).

Early in the GI Program, the TWAs were modified to include a local feedback loop using tachometers. This feedback loop reduces nonlinearities and improves predictability for the wheel while operating at different ranges. Experimental transfer functions between current and input voltage, as well as those between speed and input voltage, were obtained. These experimental transfer functions were then curve fit assuming a second order system in order to provide realistic models for simulations. Simulated and experimental results are given in Figure 14.

Experimental saturation limits were obtained by inputting sinusoidal signals to each wheel, at frequencies from 0.5 to 3.5 Hz in increments of 0.5 Hz, varying magnitudes from 0.5 to 2.5 V in increments of 0.5 V. Current and speed data was taken for each of the combinations of frequency and magnitude. Both the speed and current saturation limits are plotted in Figure 15. The experimental values shown indicate the voltage for each frequency at which saturation first occurs. From the figure, it can be seen that for frequencies less than 1 Hz, the torque wheel is speed saturated, whereas for frequencies greater than 1 Hz, current saturation is encountered. The linear operating region is below the smallest of the two saturation curves.

For disturbance input to the structure, three Unholtz-Dickie 222 N (50-lb) shakers (Model 1) are attached to the corner-body joints at Bay 9 of the Mini-Mast.

Table 5

Mini-Mast Actuator and Sensor Summary

	ACTUATORS		SENSORS					
			Control		Truss Vibration		Disturbance	
Bay No.	Torque Wheels	Shakers	Angular Rate	Linear Accel.	Primary	Secondary	Force	Accel.
18	3		3	4	3			
17						3		
16						3		
15						3		
14					3			
13						3		
12						3		
11						3		
10			2	2	3			
9		3				3	3	3
8						3		
7						3		
6					3			
5						3		
4						3		
3						3		
2						3		
1								
TOTAL	3	3	5	6	12	39	3	3

These devices have a maximum stroke of 25 mm (1 in) peak-to-peak and a nominal armature weight of 0.26 kg (0.58 lb). The armature is suspended using linear ball bushings, and the suspension stiffness and damping are both nearly zero. They are operated in the current-feedback mode, providing a force output proportional to input voltage, independent of armature position and velocity. The shakers are oriented normal to the faces of the truss at each of the three vertices, as shown in Figure 12.

Seven types of response sensors are available on the Mini-Mast testbed. Nominal sensor characteristics are provided for quick reference in Tables 6(a) through 6(c) for the principal testbed sensors: the Servo Accelerometers, the Angular Rate Sensors, and the Kaman Displacement sensors, respectively. Additional response sensors include strain gages on diagonal truss members in Bay 1, load cells at the base of the cantilevered truss structure, torque-wheel servo-tachometers measuring wheel speed, and torque-wheel motor current monitors.

Six Sundstrand QA-1400 servo accelerometers are available for linear acceleration measurements. Four accelerometers are located on the tip platform

(Bay 18) and two are located on the mid platform (Bay 10). These sensors measure linear acceleration in the global x and y directions.

Table 6

Nominal Characteristics of Mini-Mast Sensors

Table 6 (a): Servo Accelerometers

Linear Range	± 25 g
Frequency Response	± .01 dB for 0 - 10 Hz bandwidth + .45 dB for 10 - 300 Hz bandwidth
Resonant Frequency	800 Hz
Sensitivity	250 mV/g
Threshold	1 micro-g
Linearity	0.1 per cent
Damping Ratio	0.3 - 0.8

Table 6(b): Angular Rate Sensors

Linear Range	3-- Deg/sec
Frequency Response	DC - 15 Hz
Sensitivity	30 mV/Deg/sec
Threshold	0.5 Deg/sec
Linearity	0.5 per cent

Table 6(C): Noncontacting Displacement Sensors

Characteristic	1-inch Diameter	2-inch Diameter
Linear Range	1.00 inch	2.00 inch
Frequency Response	DC - 50 kHz	DC - 50 kHz
Sensitivity	1.0 mV/mil	0.5 mV/mil
Threshold	0.1 mil	0.2 mil
Linearity	1.0 % full scale	1.0 % full scale

Three Watson angular rate sensors were originally available on the testbed providing five angular rate measurements. A three-axis angular rate sensor was located on the tip platform (Bay 18). This sensor measured pitch (about the x-axis), roll (about the y-axis), and yaw (about the z-axis). Two single-axis angular rate sensors were located on the mid-platform (Bay 10), one measuring pitch, and the other measuring roll. Equipment failures eliminated the rate sensors at Bay 10 early in the two-year Guest Investigator program; late in the program, only the Bay 18 yaw measurement was available to researchers.

Fifty-one Kaman KD-2300 noncontacting proximity probes are installed on the Mini-Mast. These devices are primarily intended for structural dynamic testing; however, 12 are connected to ARTS for control experiments under the baseline configuration. Bays 2 through 18 are each instrumented with three probes. The devices measure deflections normal to the face of the probe, which are mounted parallel to the flat face on the corner joints on the structure. Sensor orientations are illustrated in Figure 13; orientation of sensors changes for even and odd numbered bays. Two types of probes are used; one with a one-inch range, and one with a two-inch range. Bays 2 through 10 use the one-inch probes, while bays 11 though 18 use two-inch probes.

Equipment Platforms

Two equipment mounting platforms are attached to the lightweight truss structure. The square tip platform measures 1.45 meters (57 in) per side and is attached to the structure above Bay 18. The triangular mid platform is located inside the truss cross-section at Bay 10, attached to the corner-body joints with off-set brackets. Both platforms have a sandwich plate construction, measuring 3.2 cm

(1.25 in) thick and consisting of a hexagonal aluminum honeycomb core between two sheets of 0.24 cm (0.09 in) thick aluminum sheets.

The sketches of the tip plate and mid plate, provided in Figure 11, allow identification of actuator and sensor location on these equipment platforms and show the spacial relationship of the platform with respect to the truss cross-section. Abbreviations for sensor and actuator identification are those given in Table 2.

Dynamic Characteristics

The dynamic characteristics of the Mini-Mast testbed provide an adequate level of realism to permit this cantilevered truss to be used as a CSI testbed for research on future large space structures. First, low frequency normal vibrational modes provide realism. The pair of first bending modes of the structure are at approximately 0.83 Hz. Five target modes identified for control purposes are all below 10 Hz. They are the pair of first bending modes, the first torsional mode, and the pair of second bending modes.

The second important characteristic adding realism to the testbed is a cluster of localized modes, consisting of 113 vibrational modes between the second bending modes, at approximately 6.5 Hz, and the second torsion mode, at approximately 22 Hz. This cluster is primarily 108 "local" or "diagonal" modes. The mass of the mid-diagonal hinge causes by the first bending mode of diagonal truss members to be at a much lower frequency than the bending modes for the longerons or battens. The diagonal modes in the cluster are interspersed with the first axial mode of the truss and several plate modes of the equipment mounting platforms. The problem of clustered local modes is anticipated for future large space structures, such as clusters of solar array modes with Space Station Freedom.

It is important to note, however, that the diagonal modes do not involve the bending of only a single diagonal, but rather show localized displacements along the entire length of the structure. Figure 16 shows the analytical mode shape for a typical diagonal mode, together with the five target modes for control purposes.

Control Law Implementation Process

User defined control laws are incorporated into a generic control software for implementation on the testbed. A great deal of flexibility has been incorporated into the generic control law, including selection of actuators to be used, type of excitation signal, mode of testing (open or closed loop), and data output. In addition, any subset of the 35 available sensors may be selected, including using the full complement. Input to and output from the control laws can be considered as engineering units or as voltage, with appropriate conversions provided through the simulation and real-time computational software. Further, the capability exists for the torque wheel actuator excitation commands to be combined with the controller commands when the excitation test time and controller test time overlap. This section will discuss both the real-time hardware and the control software.

CAMAC and ARTS Hardware

The control computer used for Mini-Mast testing is one of two CYBER 175 computers located at LaRC. Each of these computers has the power of 10 VAX MIPS or scalar LINPACK of 2.1 megaflops at 60 bits of precision. These computers are interfaced to the Mini-Mast facility via the Computer Automated Measurement and Control (CAMAC) ring network in place at LaRC, used for the ARTS system.

The CAMAC network allows transmission of sensor outputs and actuator commands at a rate of 50 megabits/second between the local A/D and D/A converters and the remote control computer via a fiber-optic data link. (CAMAC is an internationally accepted interface standard (IEEE-583) offering increased system flexibility, reduced hardware and software efforts, and increased system longevity.

The CAMAC crate built-in filters are three-pole Bessel filters, with available cutoff frequencies of 10, 20, 50, and 100 Hertz. Because of 60 Hertz noise, it is suggested that the CAMAC crate filters be set no higher than 20 Hertz. If higher analog filter settings are used, the highest allowed digital sample rate is 50 Hertz to prevent the 60 Hertz aliasing from destabilizing the Mini-Mast system. CAMAC crate analog filter cutoff frequencies should be specified on the Guest Investigator's test plan.

The minimum real-time frame rate achievable on the system is 5 msec (200 Hertz sample frequency), with 1.4 msec of this time available for control law computation. Figure 17 shows the computation time available for other frame rates. Testbed users are required to ensure their control laws will execute in the time allotted at the selected frame rate. To this end, pre-experiment testing will allow the selection of the correct frame rate.

The ARTS system can operate at the following digital sample rates: 50, 62.5, 66.6667, 80, 83.3333, 100, 125, 133.33, 166.66, 200 Hertz. For sample rates greater than 80 Hertz, advance notice must be given at least four weeks prior to a Guest Investigator's planned visit. This is required since the ARTS system runs multiple jobs and advanced scheduling is required to obtain maximum use of the system. Occasionally, sample rates higher than 80 Hertz can only be scheduled after normal working hours (i.e. after 5 p.m.).

Mini-Mast Control Program

The Mini-Mast control software is a FORTRAN 5 program developed to permit both vibration suppression and system identification experiments on the Mini-Mast. The program provides a variety of functions including several types of excitation signals, selection of the open- and closed-loop mode of testing, digital filtering capability, use of a generic linear control law formulation, software safety checks, and test data file generation. Each function is described below.

Excitation Signals

Various types of excitation signals can be generated for the actuators. These include sinusoidal, random, impulse, and user specified from an input file.

Sinusoidal excitations have several options available. First, a stepped sine wave can be used, in which the user selects start frequency, stop frequency, frequency increment (increasing or decreasing), frequency step duration and actuator(s). Default values are also available for sine frequency and amplitude selections to individually excite the first five modes of the Mini-Mast, using the most effective actuator for each mode. Finally, a general sine wave capability can be used in which the user selects an arbitrary frequency, amplitude, and actuator.

The random excitation command capability generates near white noise random signals for the selected actuator(s). Options available include setting the maximum amplitude of the commands, selecting the actuator(s) to be used, and choosing the time step for calculating and updating the actuator commands. The time step is chosen with respect to the selected frame rate, in multiples of the frame iterations. For example, if the system were run at a 0.02 sec time step, the random commands could be calculated each fifth time step (every 0.1 sec).

The impulse excitation command capability allows pulse commands to be generated for selected actuator(s). Pulse duration is an option and can range from one time step (an "impulse") to any time less than or equal to the complete test time. Pulse duration must be in increments of the system frame rate. The amplitude of the pulse is also a required input.

The user specified excitation capability allows the use of researcher-generated actuator commands. For this option, a pre-defined ASCII data file containing actuator commands for each time step is read into an array prior to the experiment and then accessed during the test to output the commands to the actuators. The program accepts either torque wheel or shaker command arrays (not both), with a maximum array dimension of (2000,3).

Modes of Testing

The Mini-Mast control program includes the *open loop* and *closed loop* modes for experiments. In a typical test scenario, sensor biases are taken first and then the open loop test is run, using the selected excitation parameters. After the excitation commands cease, the Mini-Mast is allowed to free-decay until the selected test time has been exceeded. Sensor biases are taken again if desired, and then the closed loop test is run, using the same Mini-Mast excitation commands that were input to the structure in the open-loop test. Preselected times can be included in the program to turn the controller on or off; controller commands calculated by the generic control law equations are output to the actuators only during the controller "on" time.

At the completion of the test, the software enters the *reset* mode during which variables are reset to their initial values where needed. Test definition, excitation data file changes and/or alternate control law input, variable checking, and data file generation are all performed in reset mode.

Sensor biases are obtained in the *monitor* mode by taking the average of the sensor values for each sensor for 1000 program iterations. Sensor RMS noise calculation is an option. Sensor scale factors are provided by the user prior to the test.

Generic Control Law

The linear Generic Control Law (GCL) subroutines allow testing of different controller designs via database changes to a single set of generic algorithms. These routines are identical to those that were planned for use in a previous (cancelled) flight program, Control of Flexible Structures (COFS I).

The GCL subroutines are initialized by a series of matrices read in from an external ASCII file prior to the testing. The control law input data file requires the number of actuators used in the controller, the number of sensor inputs to the control law, controller input vector definition, and the controller matrices (A, B, C, D, E, and F), packed by columns, followed by any filter coefficients used. This data file is assembled by LaRC personnel based on controller information provided with the test plan which must be submitted prior to any visit. For ease of control law implementation on the Mini-Mast real-time computer system, it is requested that the controller matrices be discretized at the desired sample rate and provided in the PACKED-BY-COLUMNS FORMAT. The software defaults to the appropriate scale factors and biases for the interface with the Mini-Mast. Researchers can provide alternate scale factors if required by a particular control law.

The researcher has the option to use the whole or any subset of the following GCL routines described to support the experiment. The first routine described is a digital filter implemented as an Auto-Regressive Moving Average (ARMA) to provide filtered Mini Mast sensor outputs if desired.

The filter is based on the following:

$$Z(i,k) = \sum_{j=1}^{m_s(i)} P_s(i,j) * Z(i,k-j) + \sum_{j=0}^{n_s(i)} Q_s(i,j) * Y(i,k-j)$$

where
$Z(i,k)$ = Filtered sensor i output at time sample k.
$Y(i,k)$ = Sensor output i at time sample k.
$P_s(i,j)$ = Auto-regressive coefficient j for sensor i output.
$Q_s(i,j)$ = Moving average coefficient j for sensor i output.
$m_s(i)$ = Maximum order of filter for sensor i.
$n_s(i)$ = Maximum order of averaging for sensor i filter.

The other filter routine is an ARMA implementation used to digitally filter the generated actuator commands. Its equation is as follows:

$$V(i,k) = \sum_{j=1}^{m_a(i)} P_a(i,j) * V(i,k-j) + \sum_{j=0}^{n_a(i)} Q_a(i,j) * U(i,k-j)$$

where
$V(i,k)$ = Filtered command for actuator i at time sample k.
$U(i,k)$ = Controller command for actuator i at time sample k.
$P_a(i,j)$ = Auto-regressive coefficient j for actuator i.
$Q_a(i,j)$ = Moving average coefficient j for actuator i.
$m_a(i)$ = Maximum order of filter for actuator i.
$n_a(i)$ = Maximum order of averaging for actuator i filter.

The actuator commands are calculated using the following linear control law implementation:

$$U = D * X + E * U + F * Z \quad \text{(Output)}$$

$$X = A * X + B * U + C * Z \quad \text{(State Equation)}$$

where
A = constant matrix, state * state.
B = constant matrix, state * actuators.
C = constant matrix, state * sensors.
D = constant matrix, actuators * state.
E = constant matrix, actuators * actuators.
F = constant matrix, actuators * sensors.
X = column vector of controller states at time k.
U = controller column vector at time k.
Z = filtered sensor outputs from Mini-Mast at time k.

Appropriate limits included in the software ensure that all actuator commands are within acceptable bounds.

Experimental Data Output

Experimental data is available to the researcher two ways -- 16 channels of strip chart recorder output and a complete ASCII data file that contains all D/A and A/D converter values for each time step of the test.

The console strip chart recorders can output any 16 of 93 pre-defined program variables in real-time during testing. To simplify use of the strip chart recorders, the software has an auto-scaling feature that allows maximum use of the $\pm$ 2.5 volt input range.

Numerical data written to the real-time disk during a test can be output to a local ASCII file whenever the program is in the RESET mode. Up to 99 sequentially numbered data files can be generated for each set of test runs. During PRINT mode, the operator is prompted for a unique five character file name, to which a number from 00 to 99 is appended to specify different test runs during a single session. The operator is then prompted to enter a descriptive header, if desired, after which the test data on the real-time disk is spooled to a local file. When testing is complete, the data files are available to be transferred to other computers or storage devices for post-processing.

Safeguarding the Testbed

Since the torque wheel actuators on the tip platform have the capability of breaking the structure, a comprehensive set of safety limits is necessary to safeguard the test article. First, analytical simulations are performed by NASA personnel for each control law before approval is granted to implement that control law on the testbed. Then during the actual test, the control program monitors all sensor outputs and actuator commands, shutting down the system if safety limits are exceeded. Finally, analog safety devices installed on the truss continually monitor structural response and initiate the system shutdown if limits are exceeded.

The safety limits are based on critical member loads. Table 7 provides information on critical axial loads, critical stress, and critical strains for longerons, battens and diagonals. These load limits severely restrict the maximum allowable truss deflection and twist based, such that the tip (Bay 18) is allowed to deflect only 0.3 inches and to rotate only 0.15 degrees.

Table 7

Critical Member Loads

Member	σ_{crit}	P_{crit}	M_{crit}
Diagonals	5.05E7 N/m^2	800 N	11.97 Nm
Longerons	5.05E7 N/m^2	5600 N	28.74 Nm
Battens	5.05E7 N/m^2	12000 N	10.54 Nm

Analytical Safety Checks

Analytical safety checks are performed to verify both the control law stability and the member loads imparted to the structure during closed-loop analysis. NASA researchers approve implementation of an experiment only after closed-loop simulations have been verified as stable and structural member loads have been verified as safe. The Integrated Multidisciplinary Analysis Tool (IMAT) is used for the closed-loop simulations,[4] in addition to MATLAB simulations. The structural integrity of Mini-Mast is verified using the IMAT physical data recovery process whereby structural member loads are calculated from time histories of actuator forces generated during closed loop simulations. After approval, further analytical safety checks are conducted with the ARTS system real-time computer system and the generic control law subroutines.

IMAT simulation tools are available to Mini-Mast Guest Investigators (GIs), in addition to being used by NASA researchers to approve control laws for testing. A cluster of seven DEC MicroVaxes contains a set of commercial codes (including

NASTRAN, MATRIXx, SYSTEM_BUILD, I-DEAS, and DI-3000) for engineering data storage and retrieval, structural modeling and analysis, and controls design and analysis. These codes, together with pre- and post-processors, are combined in IMAT under control of a menu-driven executive program. GIs are authorized to use IMAT to access Mini-Mast modes and frequencies from a controlled database, create state space vectors using modes of interest, design control systems, and perform closed-loop dynamic simulations using MATRIXx and SYSTEM_BUILD. Several application examples and a comprehensive User's Guide are available.[3,4]

Use of IMAT by GIs is limited to Mini-Mast research. Also, due to contractual restrictions, the MSC/NASTRAN software on IMAT is not available to researchers working at their respective university or industry locations unless they already own a MSC/NASTRAN license; however, the software will be available to all investigators working *on site* at the NASA LaRC. The RIM database containing MSC/NASTRAN modal results, necessary as input to the controls package, will be available to all investigators, regardless of license ownership. Obtaining an account on IMAT should be handled through the technical monitor for the research grant or contract . Full software documentation is available on site; copies of some documentation can be provided to individual researchers, as well.

Both off-line and real-time simulations are also performed on the ARTS system. A modal simulation of the Mini-Mast, using the current finite element model together with models of actuator and sensor dynamics, is used for off-line pre-experiment checks of control algorithm performance and timing studies.

The real-time ARTS simulations provide the final safety check before a control law is implemented. A "pseudo closed-loop" test is the final check; it verifies that the control law loaded into the real-time computer is the same as the control law included in the IMAT simulation (where the structural integrity check was performed). During the "pseudo closed-loop" simulation, the preselected disturbance which will be used later in the closed-loop tests is first applied to the actual test article in the open loop mode. Feedback signals from the structure are fed through bessel filters into the control law on the real-time computer. However, output signals from the control law are saved as time histories instead of commanding the torque wheel actuators. This same sequence is followed through IMAT with MATRIXx. Comparing the time histories highlights potential discrepancies between the control law as loaded into each system.

Software Safety Checks

During all real-time closed-loop operations, the Mini-Mast generic control law software performs safety checks, monitoring all sensor outputs and all generated actuator commands. The goal of the software safety checks is to ensure shutdown conditions on the Mini-Mast facility are first detected and acted upon by the software prior to activation of the analog safety devices installed on the truss itself.

The safety check software works as follows. Absolute limits on sensor outputs are pre-defined based on structural analysis of the Mini-Mast test configuration. After an investigator has selected all test parameters and a particular disturbance signal, an open-loop test is performed. Sensor outputs in response to the system disturbance are first checked to ensure they are within the allowable limits. If the absolute limits are exceeded, the software sends a zero command to all actuators and the test is halted. The software would then print a diagnostic message, describing the reason for the shutdown. If the absolute limits are not exceeded, the maximum and minimum values obtained from each individual sensor output during the open-loop test are used to set the limits for that sensor during closed-loop testing. A nominal scale factor is applied to the limits to allow for slight transients when the controller is enabled. Individually determined sensor limits are always less than or equal to the absolute limits. If the individual sensor limits are exceeded in the closed-loop test, the actuators are once again given a zero command, the test is halted, and a diagnostic message is printed, highlighting which sensor caused of the shutdown.

Hardware Safety Checks

The final level of safety protecting the test article consists of physical devices installed on the Mini-Mast truss structure. Voltage monitors on the Kaman sensors at Bays 10, 14, and 18 continually check truss displacement. Exceeding predetermined voltage levels shuts down the system, commanding zero to all actuators. Voltage limits correspond to displacements of 0.05 inches at Bay 10, 0.175 inches at Bay 14, and 0.3 inches at Bay 18. In addition, summers at each of the three bays monitor torsion, again activating a system shut-down if appropriate levels are exceeded. Torsion limits are 0.07 degrees at Bay 10, 0.11 degrees at Bay 14, and 0.15 degrees at Bay 18.

If a voltage monitor at Bay 18 should fail to shut down the system, contact switches are physically located 0.375 inches from the tip plate, just beyond the tip displacement limit of 0.3 inches. These switches are not effective, however, in providing additional safety with regards to torsion. Contact switches are also included at Bays 10 and 17. Finally, aluminum bumpers are positioned along side the tip plate, just beyond the contact switches

The last physical monitoring system consists of strain gages installed on diagonals in Bay 1, at the root of the vertically cantilevered beam. A measurement of 25 microstrain will send a zero command to all actuators.

In the unlikely event that all safety features fail to shut down the system and a catastrophic failure occurs, physical barriers will prevent the heavily weighted tip plate and mid plate from falling. Crossbars are located just below the tip plate, to catch it in the event of truss failure. Three tether cables loosely strung between the mid plate and tip plate would suspend the mid plate from the tip plate, then resting on crossbars, if the model failed structurally.

A Strawman Control Experiment

A strawman experiment has been used to help define the baseline hardware and equipment configuration for the testbed. The control objective is to minimize the relative motion between the tip of the truss and the platform at Bay 10. A summary of the strawman experiment is provided in Figure 18.

Under the strawman proposal, all control algorithms use only the actuators and sensors located on the platforms. In particular, the 51 Kaman displacement sensors distributed along the length of the truss have been excluded. This is consistent with the analogy to in-space implementation, where sensors measuring absolute displacement with respect to ground are not available. Time histories from the displacement sensors can be used to assess control effectiveness. In particular, the relative displacements of Bays 18 and 10, adjacent to the two instrumentation platforms, would be considered as a primary criteria in the strawman control experiment. The rms value of the closed-loop relative displacement responses with respect to the corresponding open-loop values, expressed in dB, could be calculated. These results should provide a good synopsis of global vibration suppression.

This experiment should sufficiently challenge and exercise most control synthesis techniques. Because the base of Mini-Mast is constrained, minimizing the relative translations and twist between Bays 18 and 10 is analogous to minimizing the vibration amplitude at both bays simultaneously. This is a challenging requirement in the presence of broadband disturbances (e.g., 0 to 20 Hz) because the first bending and first torsion modes are maximum at Bay 18, while the second bending mode is maximum at Bay 10. In addition, all three modes have large amplitudes at the location of the disturbances, Bay 9.

This strawman proposal is meant to serve as an initial focus but is not intended to be the only experiment to be performed. In-house experiments, performed during spring and summer of 1989, provide an example of initial controls efforts on the testbed.[5]

Requests for other equipment configurations and testing procedures will be considered on an individual basis. Ensuring safety and preserving the long-term structural integrity of the truss will be the prime consideration when examining the impact of any requested changes to the equipment configuration or the testing procedure.

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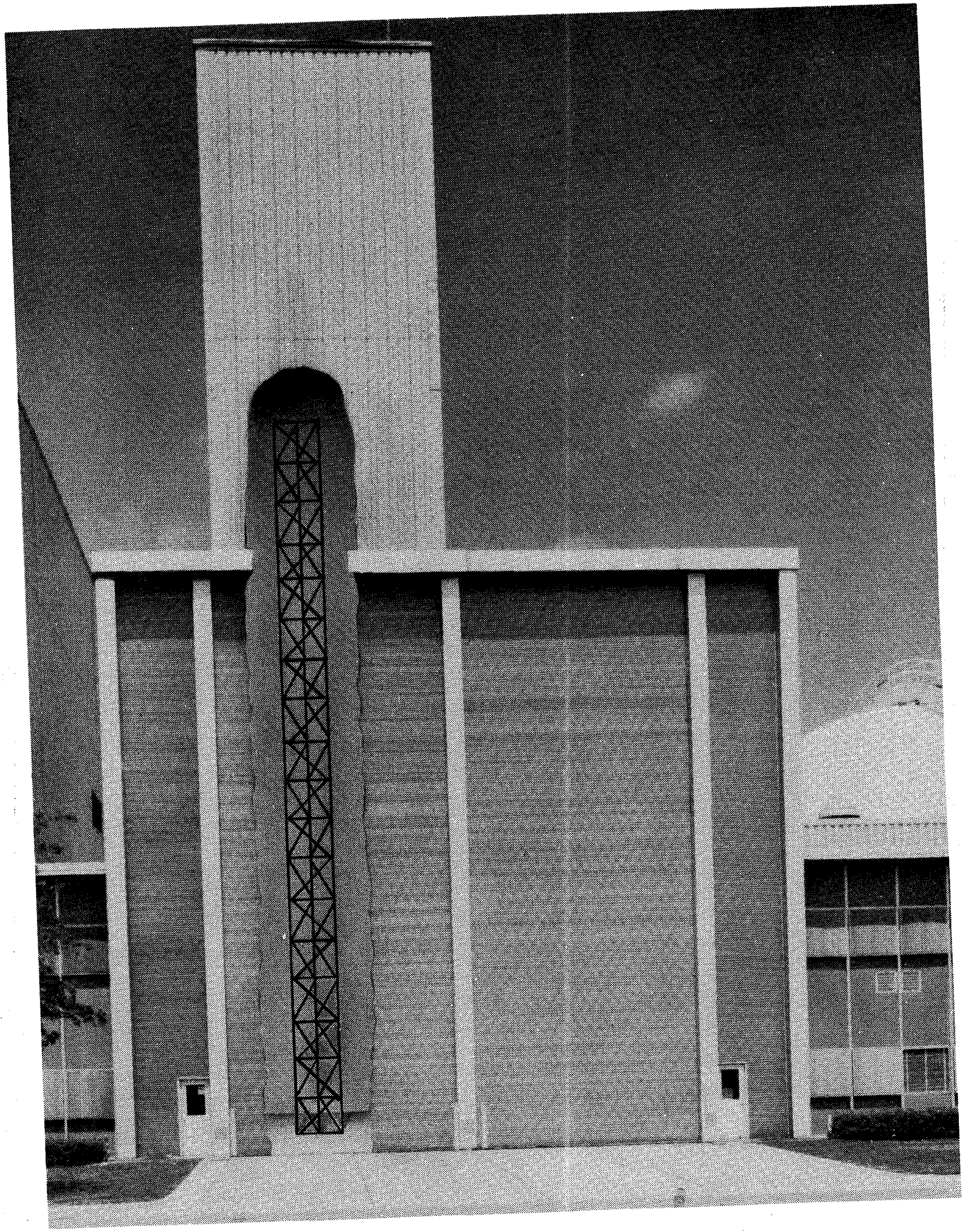


Figure 1. Mini-Mast Orientation in the High-Bay Tower of Bldg. 1293B

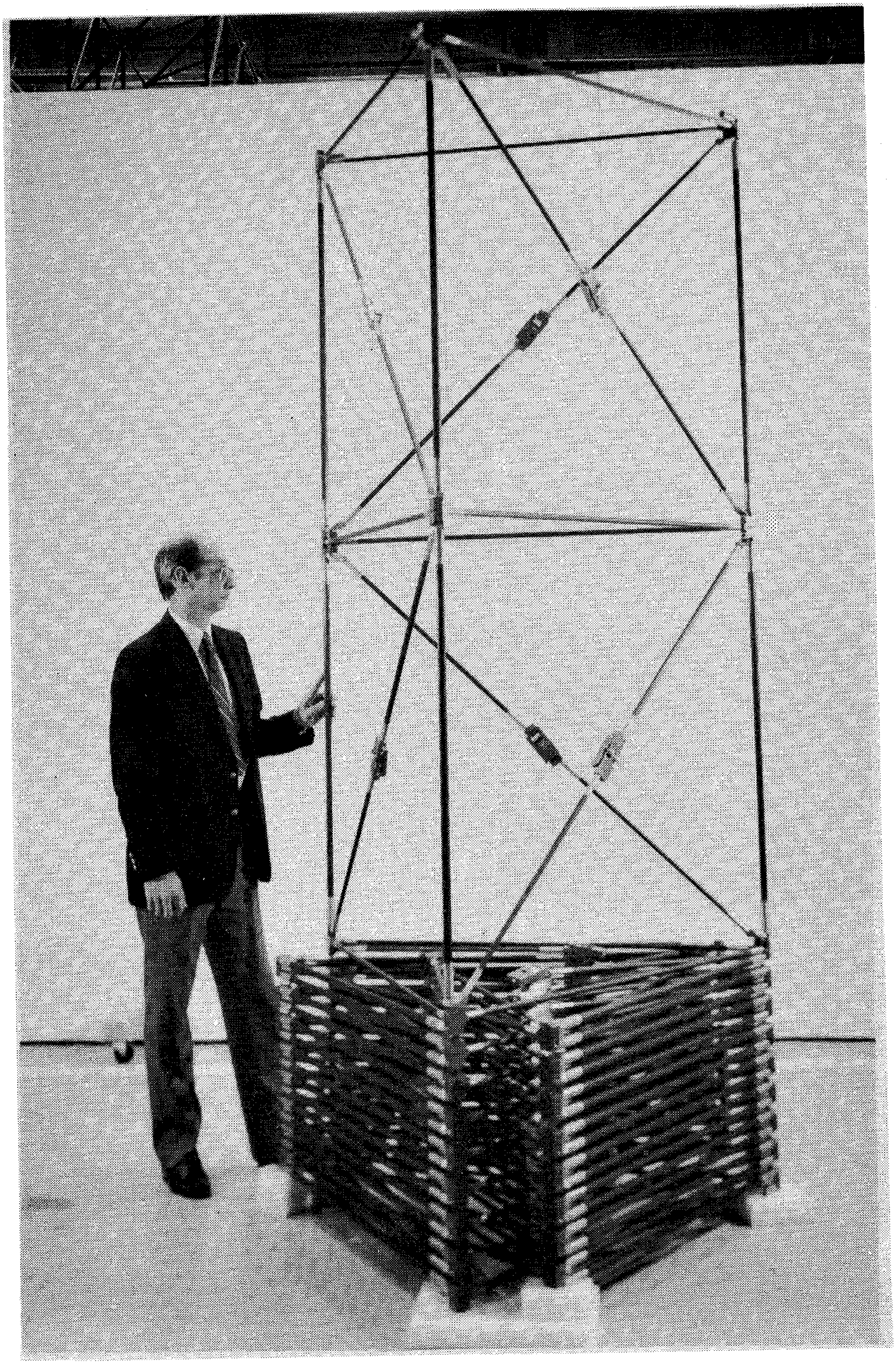


Figure 2. Preliminary Deployment of Two Bays from Folded Stack

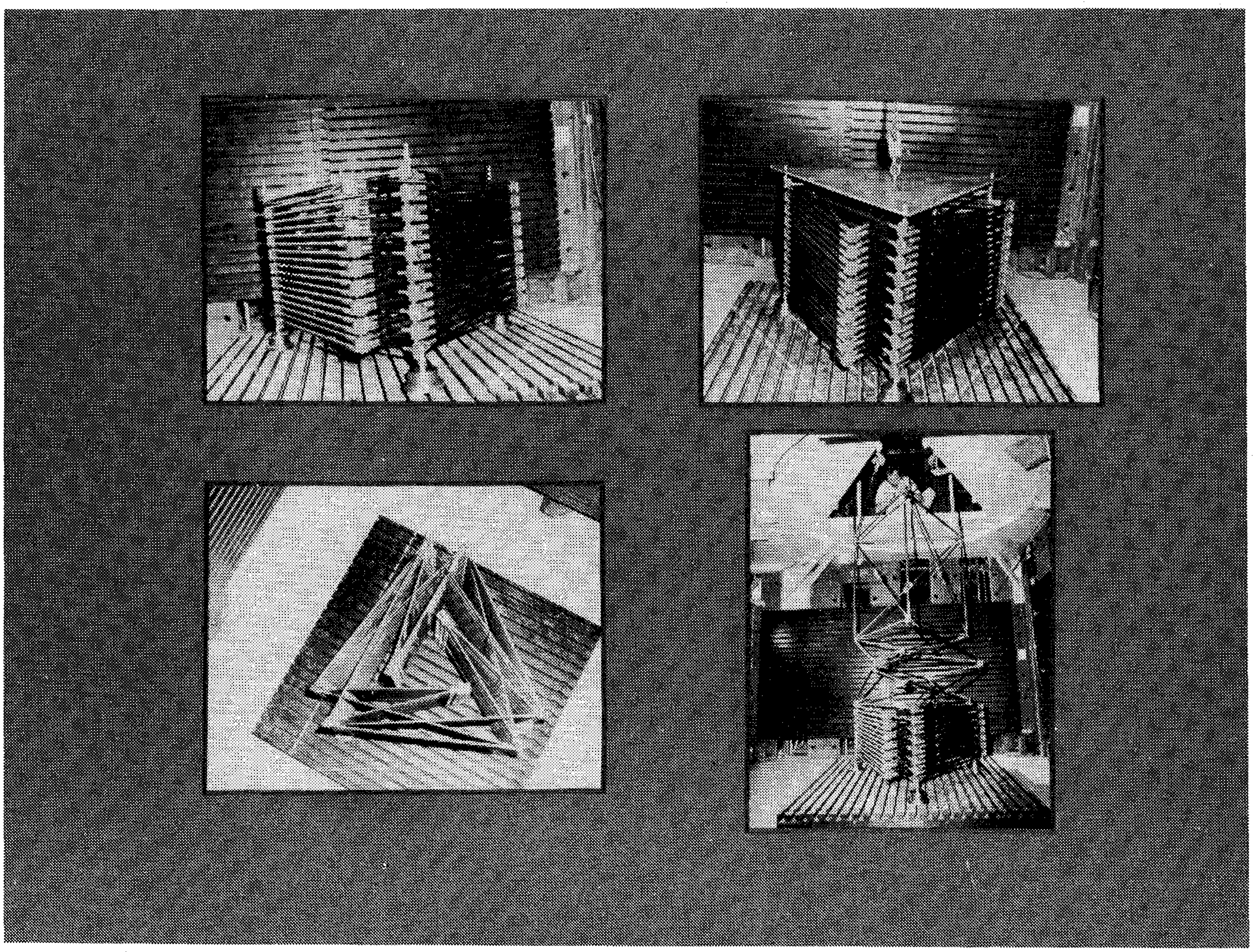
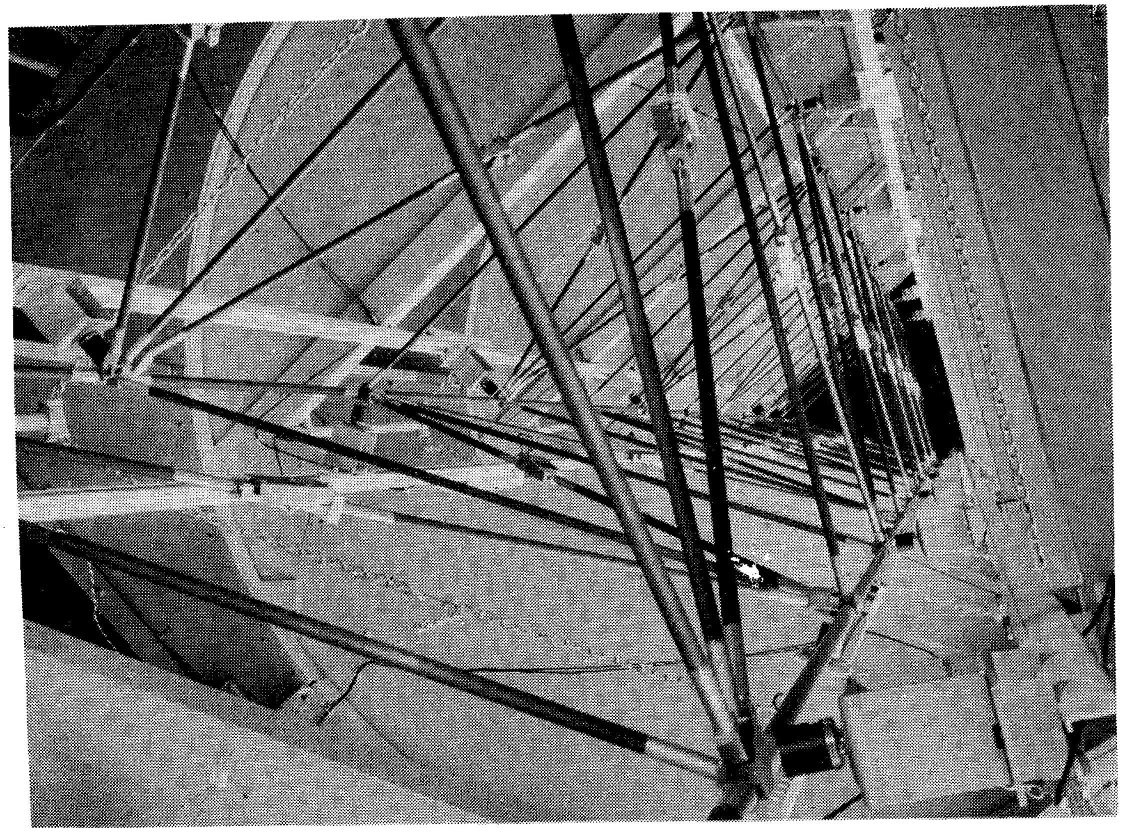


Figure 3. Deployment Sequence



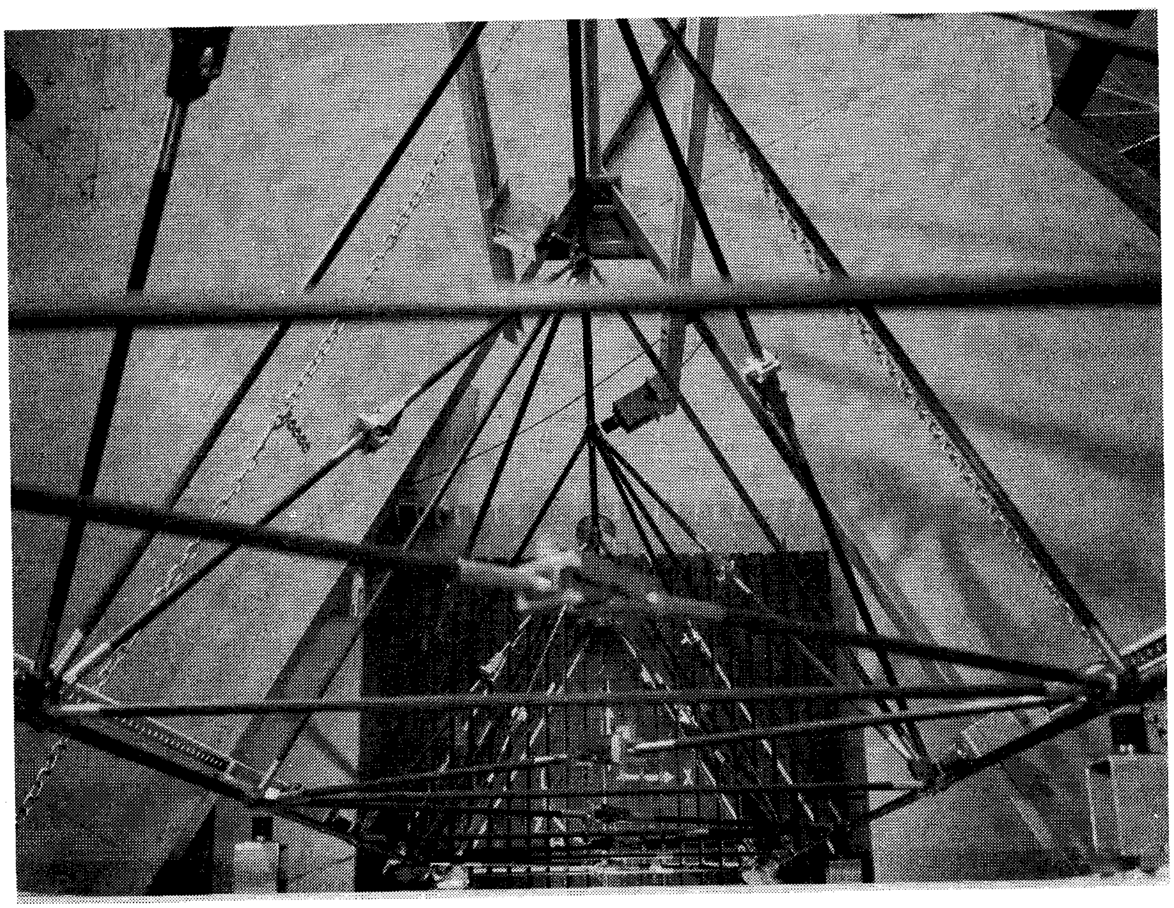


Figure 4. Perspective Views of Fully Deployed Truss Inside Tower

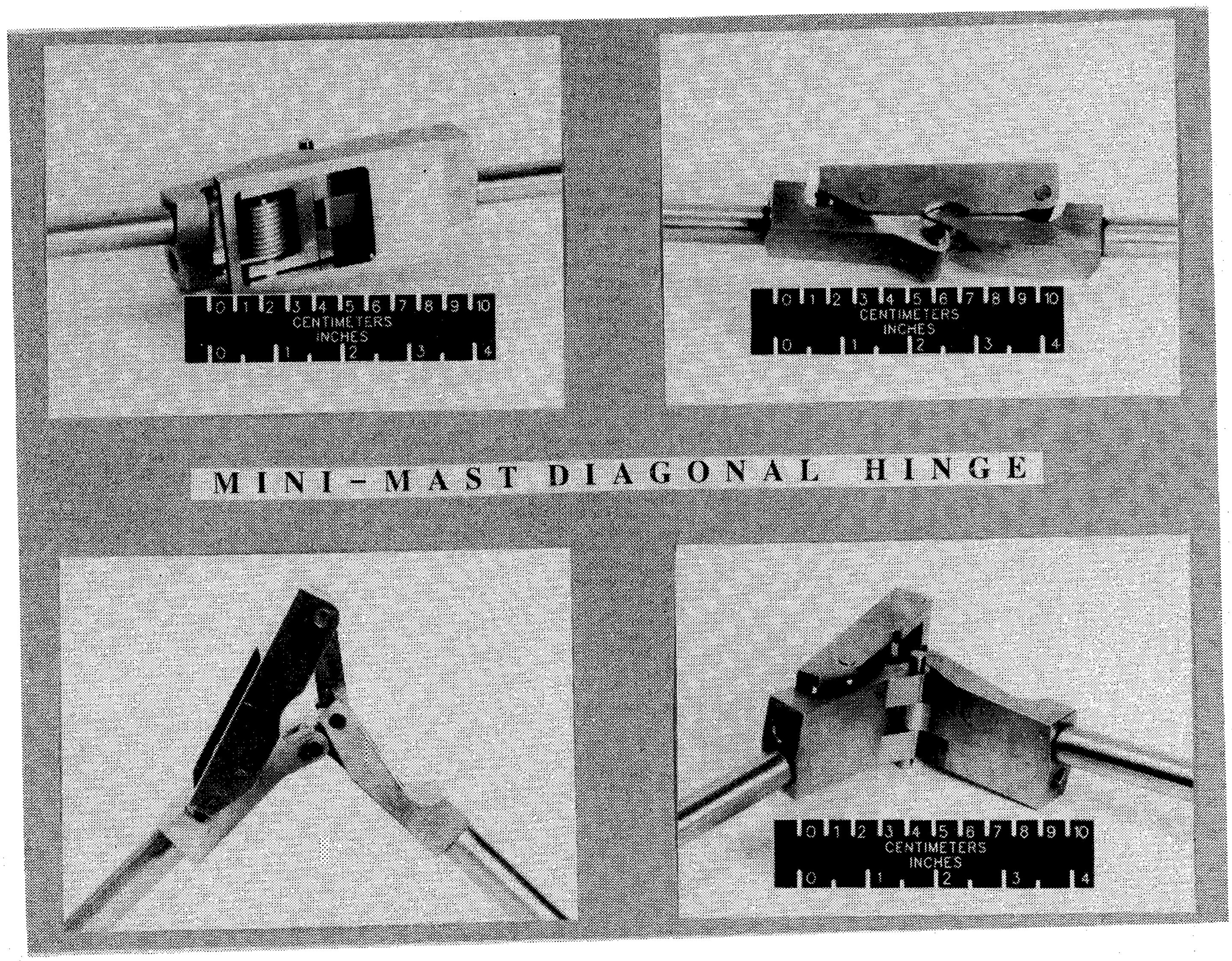


Figure 5. Mid-diagonal Hinge, Showing both Closed and Intermediate Positions

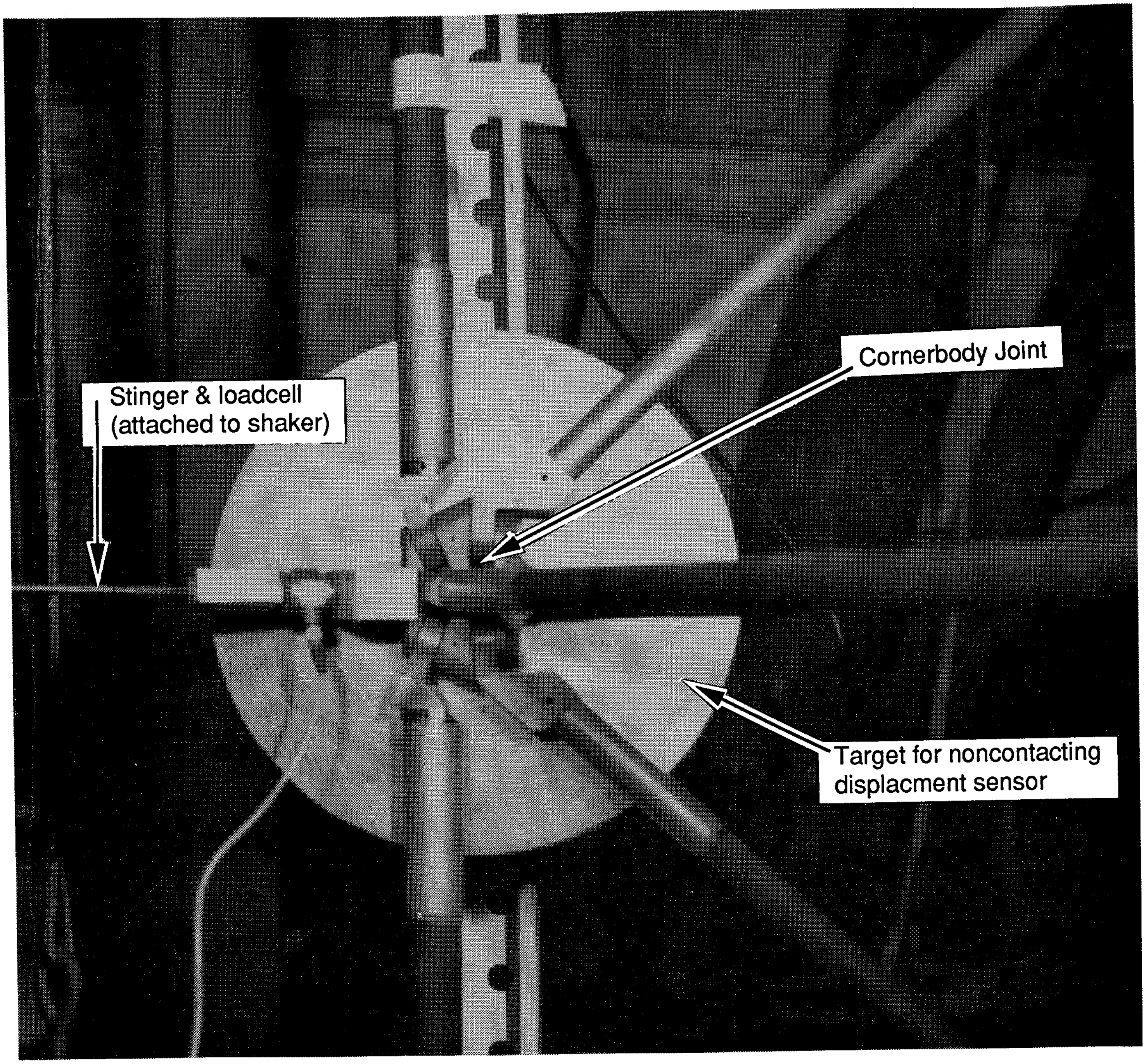


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Figure 6. Corner Body Joint with Noncontacting Sensor Targetand Shaker Attachment

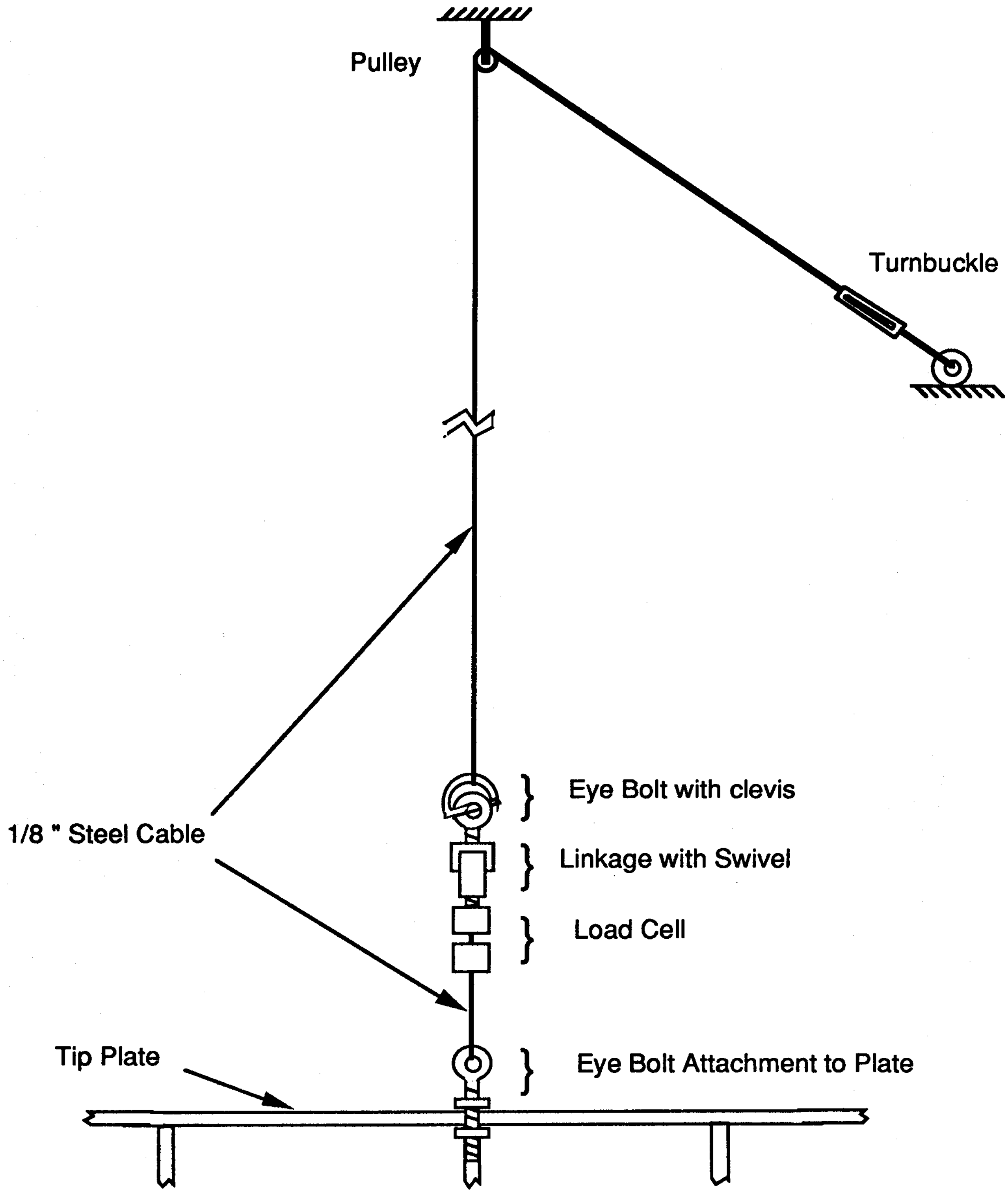

Figure 7. Cable System Off-Loading Tip Plate Mass

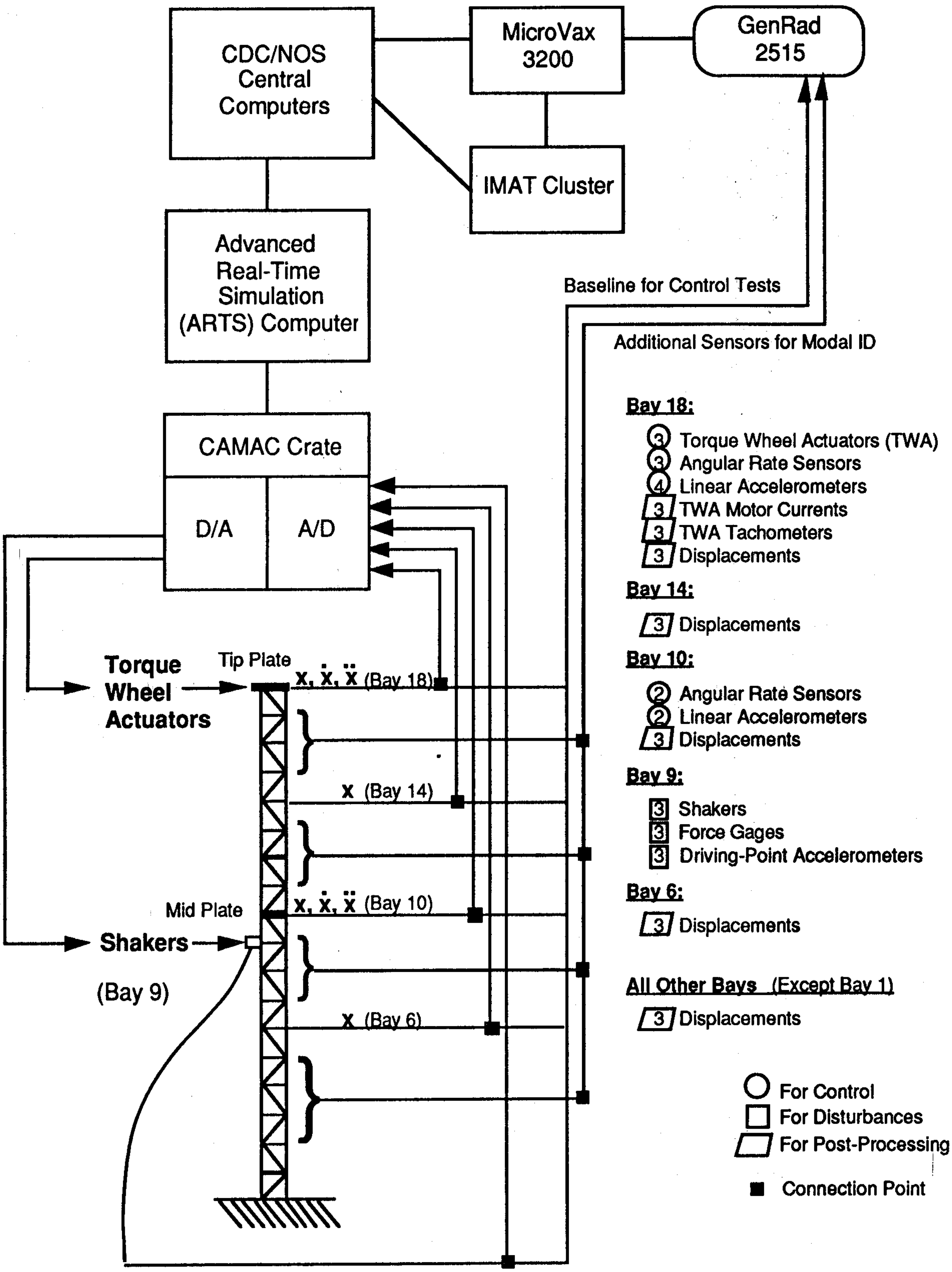

Figure 8. Baseline Equipment Configuration

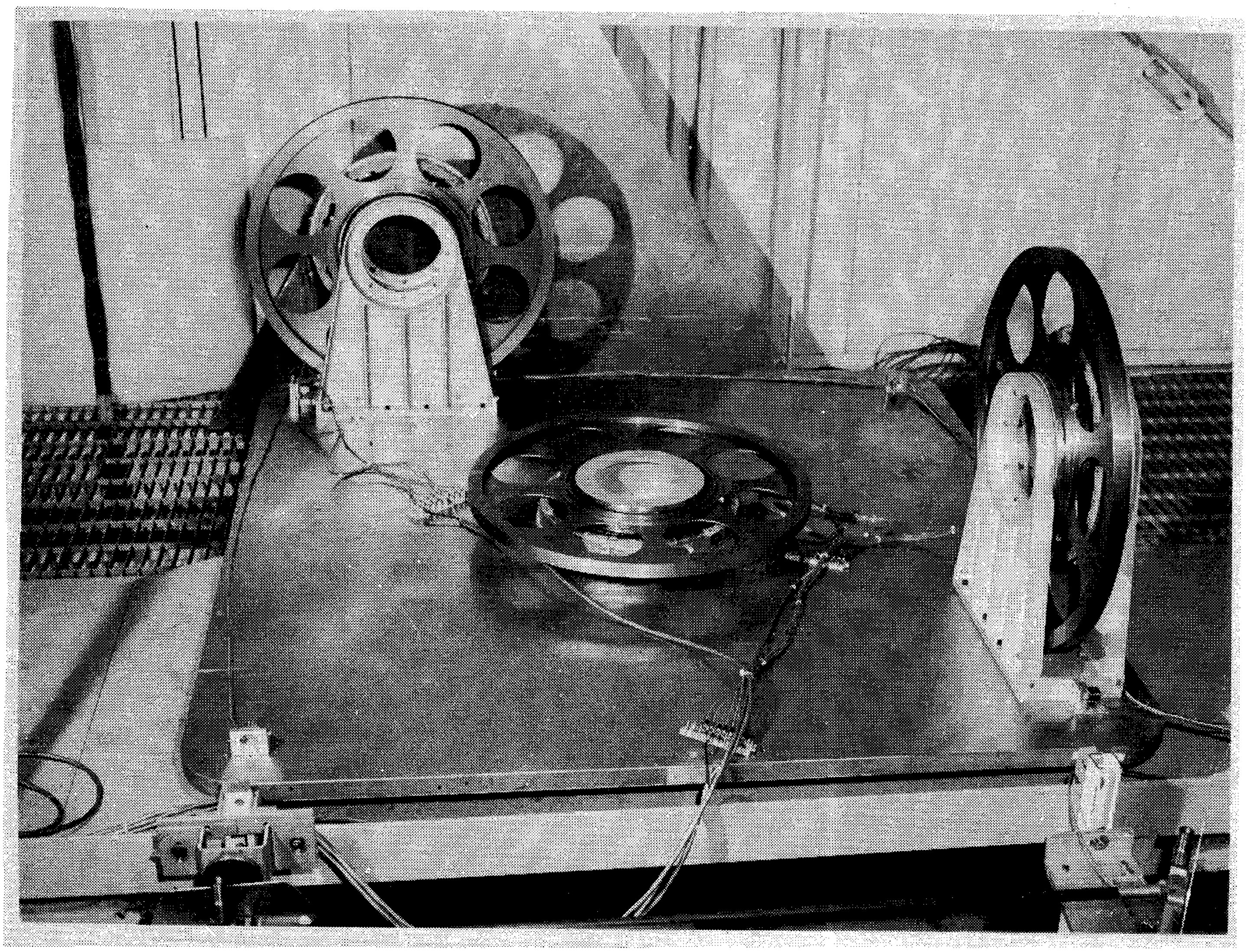

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Figure 9. Tip Plate with 50 ft-lb. Torque Wheels and Corner Accelerometers Installed

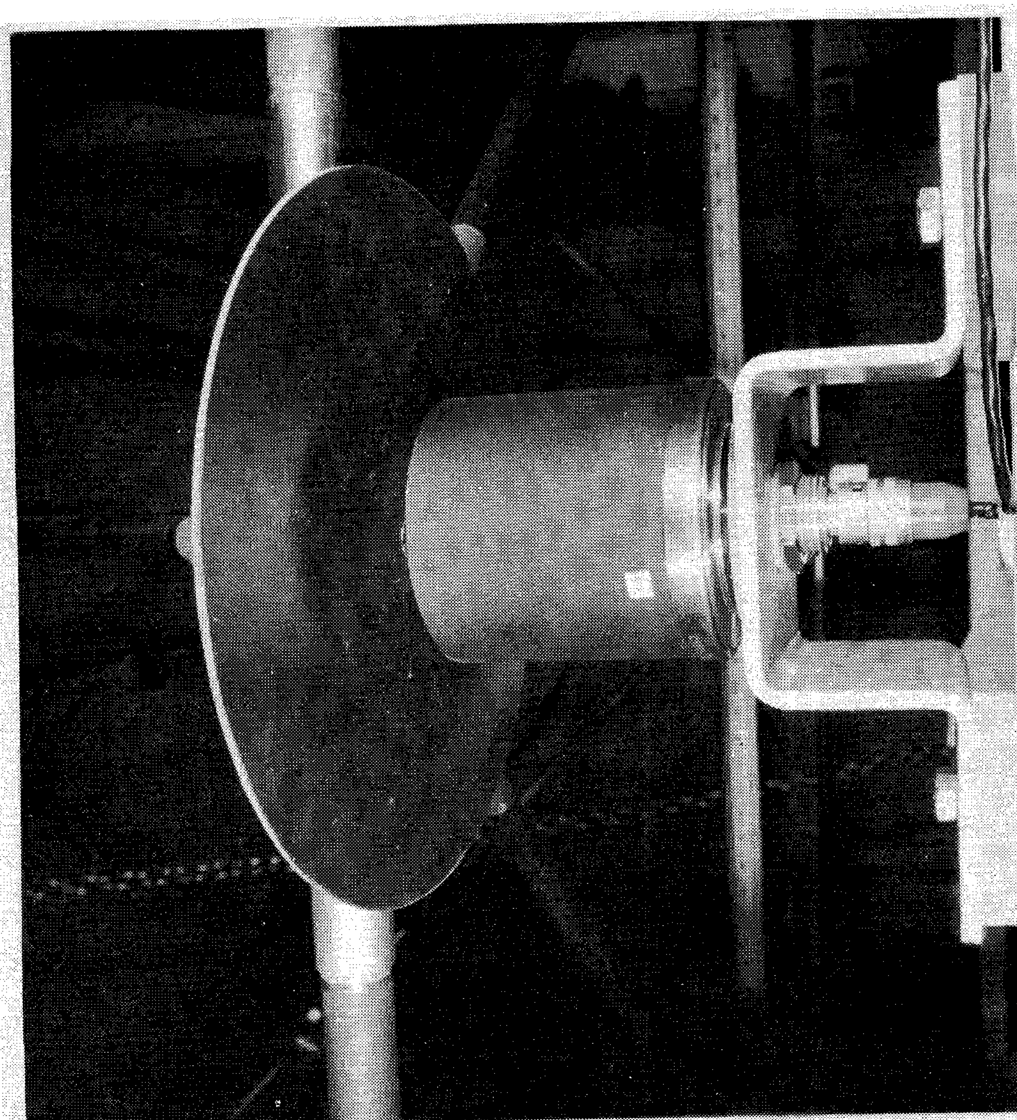

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Figure 10. Close-Up View of Two-Inch Kaman Eddy-Current Displacement Sensor

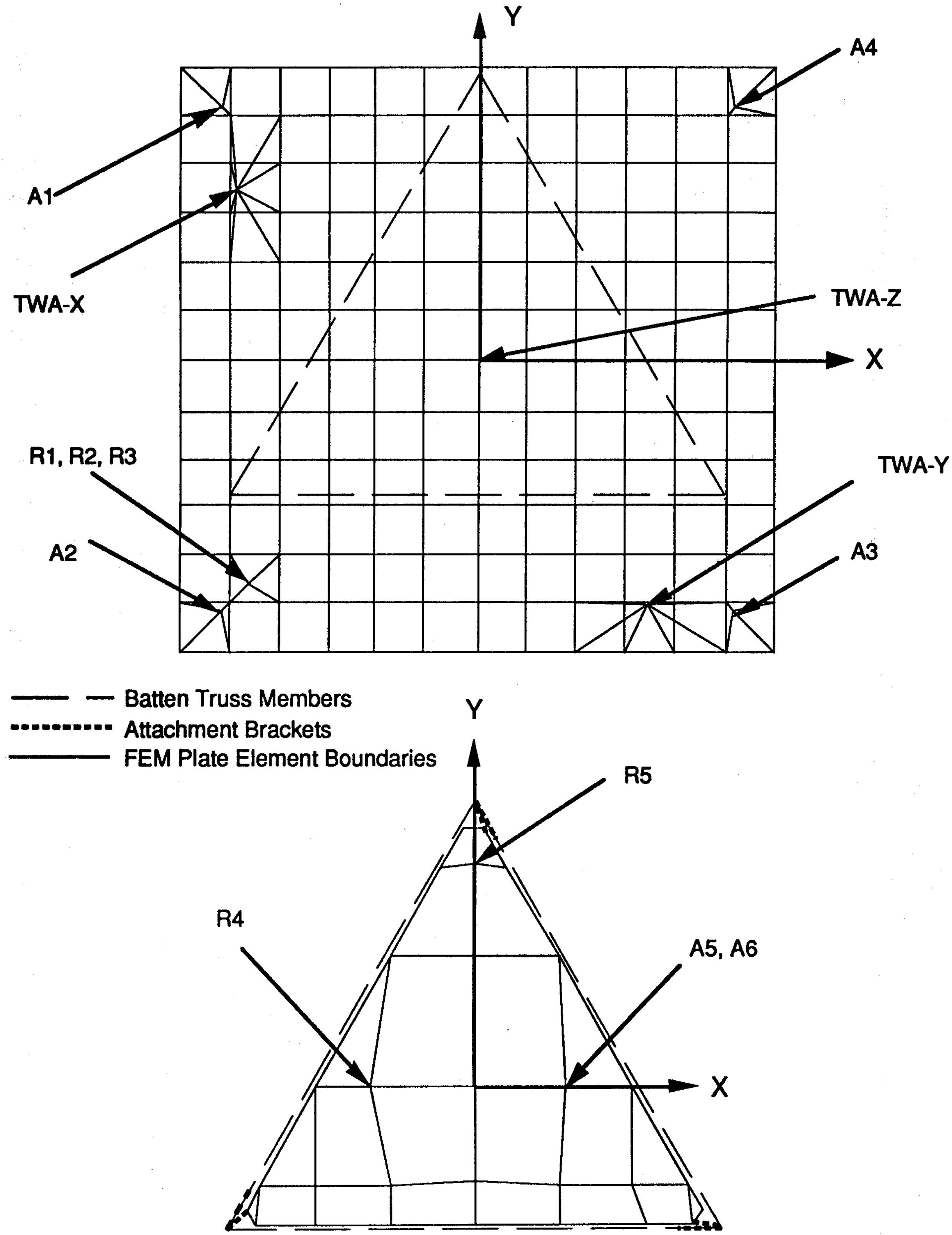


Figure 11. Actuator and Sensor Positions on the Platforms, Overhead View

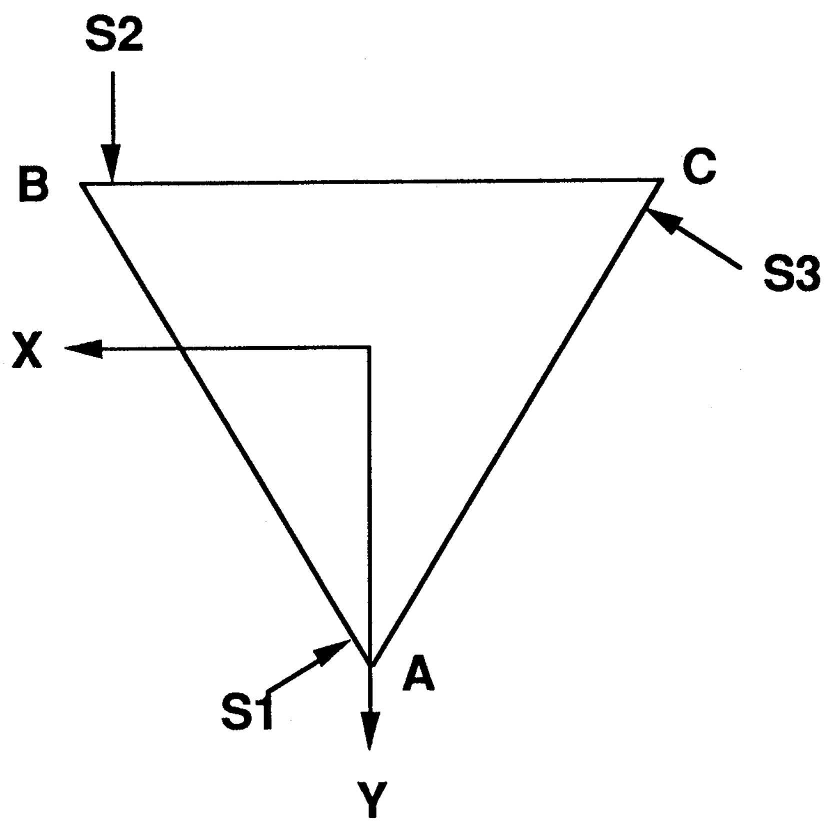


Figure 12. Shaker Positions on Bay 9

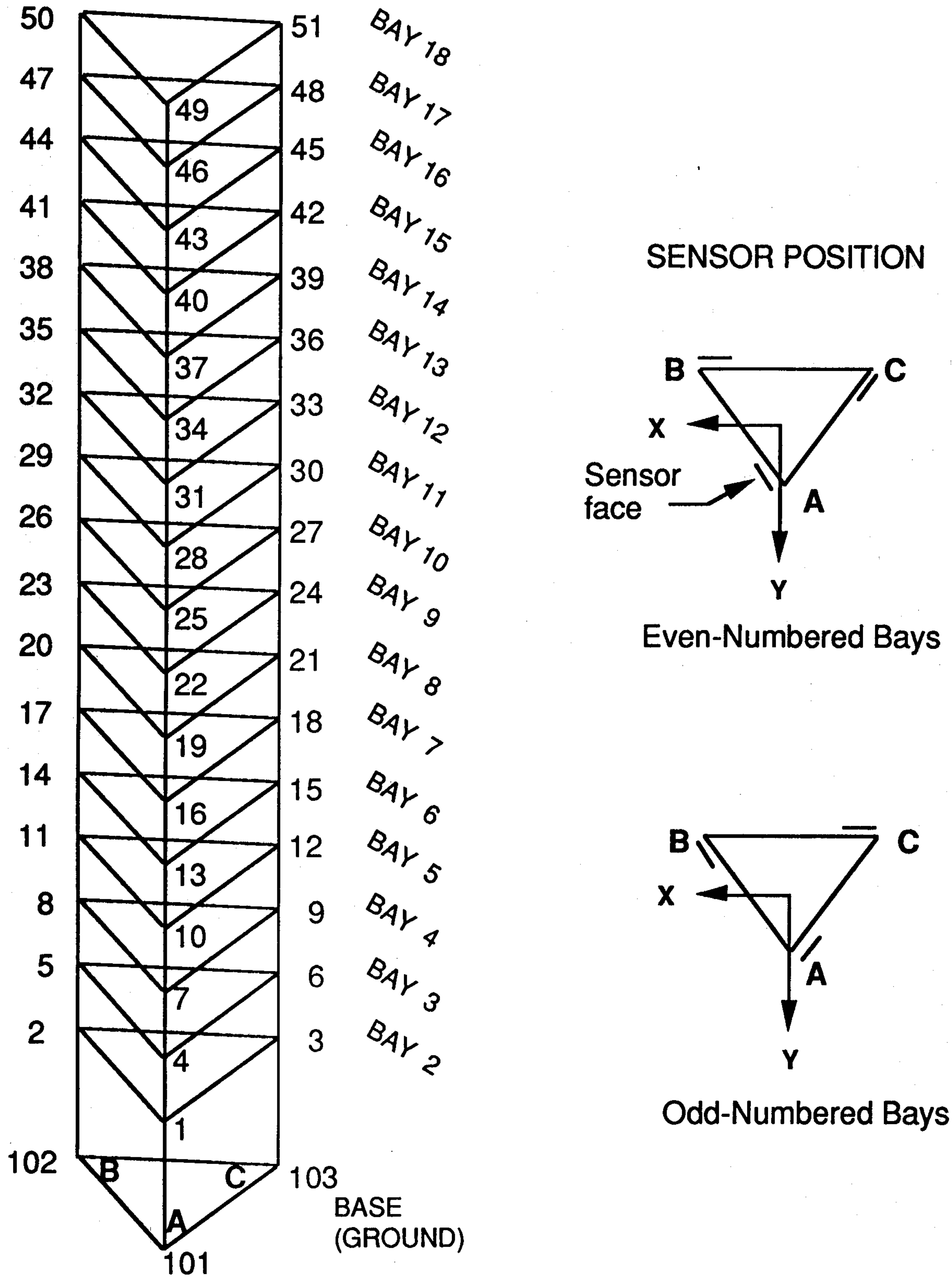
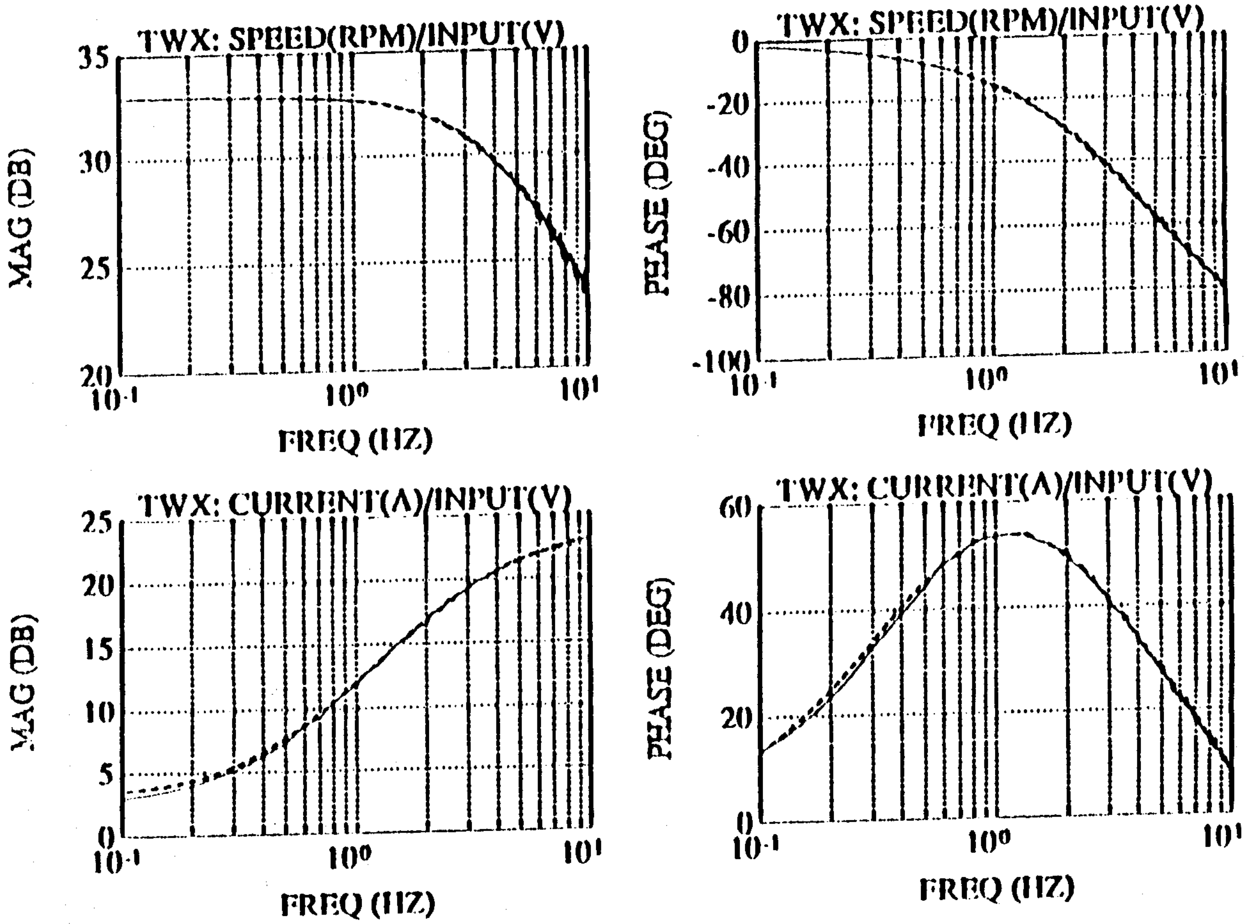


Figure 13. Location Numbers for Kaman Displacement Sensors
(Nos. 101, 102, and 103 are ground points.)



(Solid line is experimental data;
dashed line is simulation)

Figure 14. Comparison of Simulated and Experimental TWA Transfer Fuctions

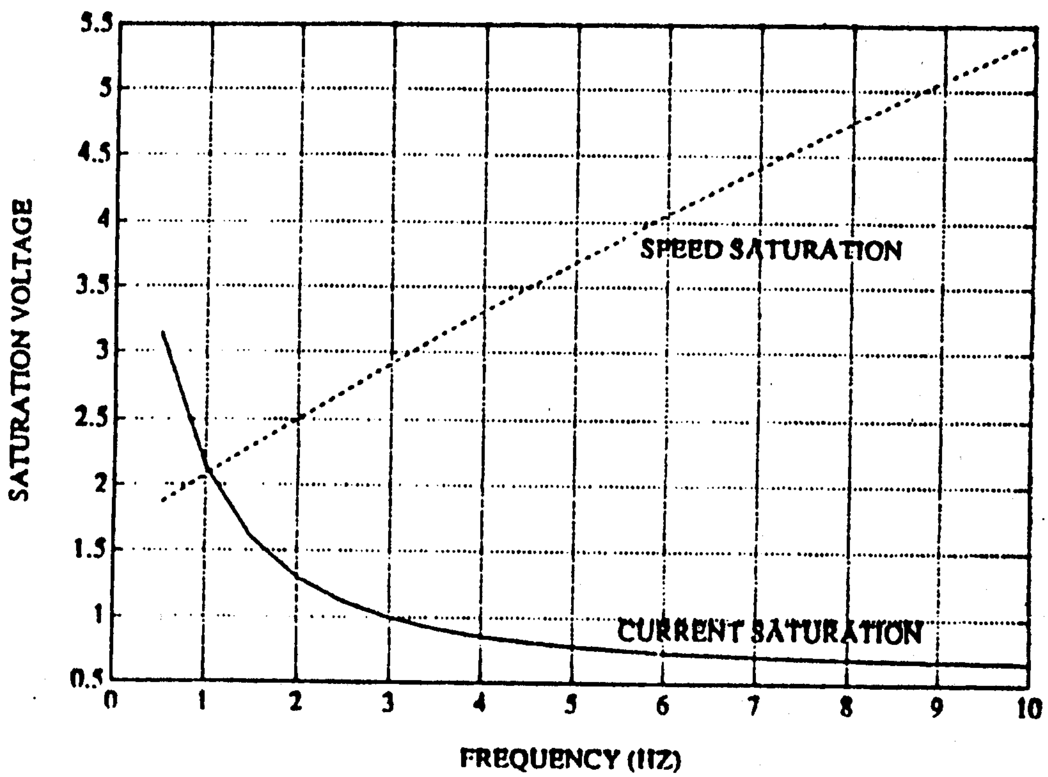
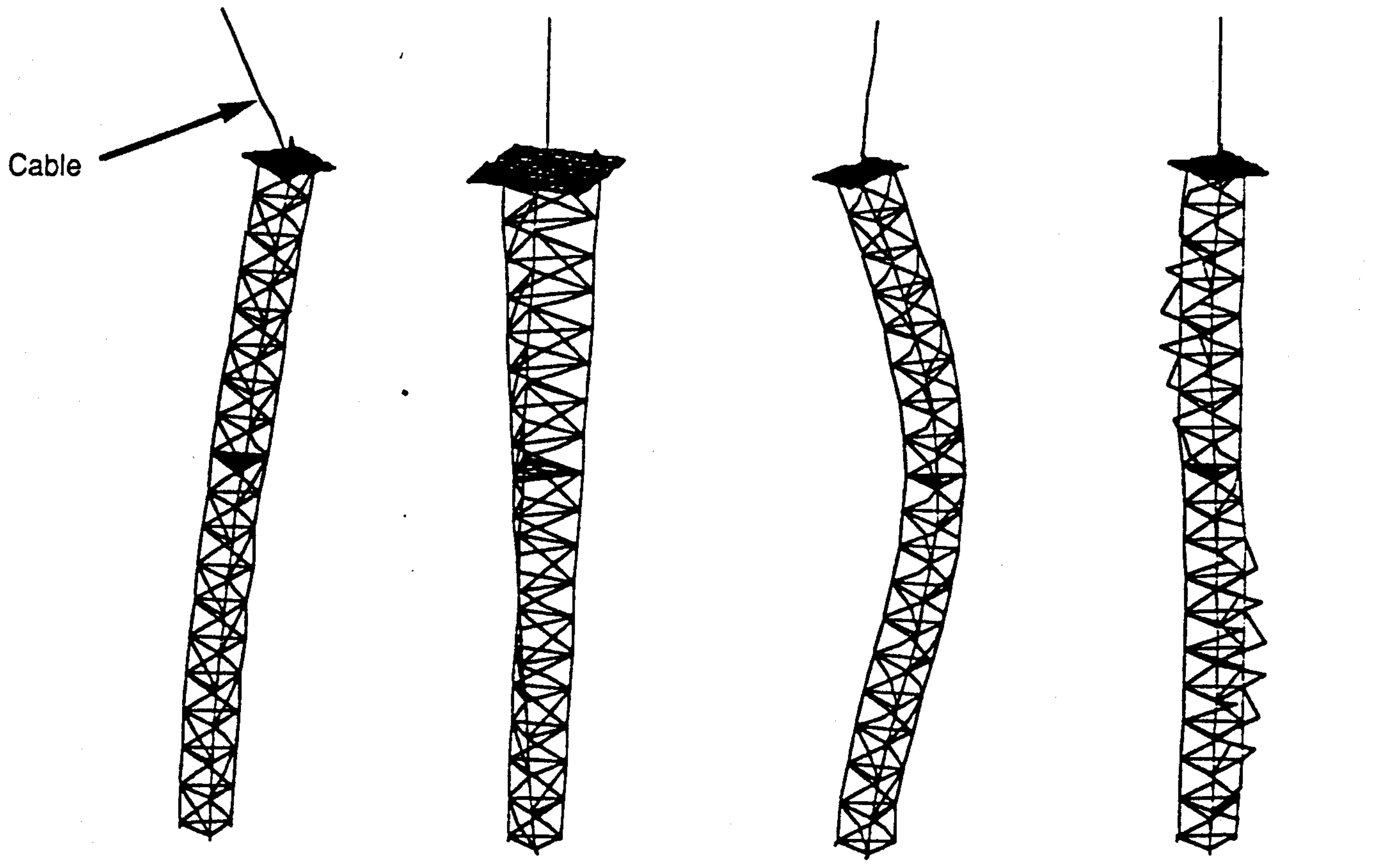
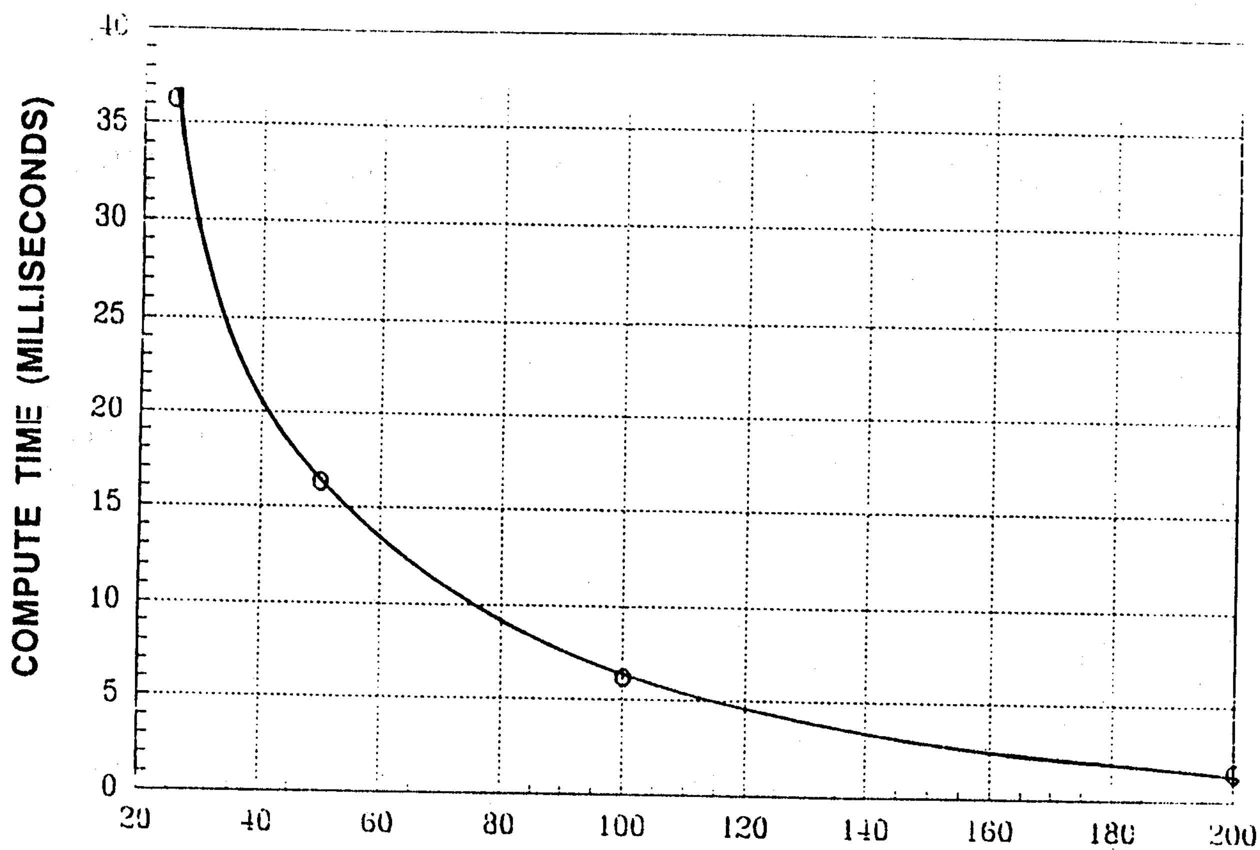


Figure 15. Torque Wheel Actuator Saturation Limits



	1st Bending	1st Torsion	2nd Bending	Typical "Diagonal" Mode
Analytical	0.80 Hz; 0.81 Hz	4.37 Hz	6.11 Hz; 6.16 Hz	14.6 - 19.7 Hz
Experimental	0.84 Hz	4.18 Hz	6.08 Hz	-----
% Difference	-4.76	4.55	0.49; 1.32	-----

Figure 16. Analytical Mode Shapes and Frequencies

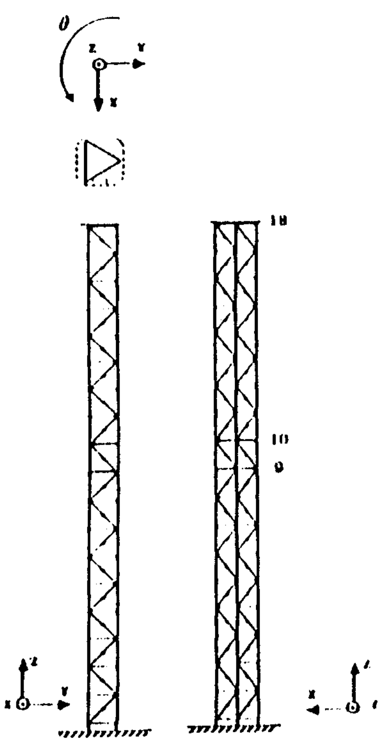


FRAME RATE (HZ)
CYBER-CAMAC CONTROL LAW TIMING REQUIREMENTS

Figure 17. compute-Time-Available on ARTS vs. Selected Frame Rate

STRAWMAN CONTROL EXPERIMENT

Mini-Mast CSI Testbed



- Minimize $|X_{18} - X_{10}|$, $|Y_{18} - Y_{10}|$, and $|\theta_{18} - \theta_{10}|$ in the Presence of Disturbances Applied at Bay 9

- Controllers Can Be Designed Using:
  - Measured Disturbances
  - Unmeasured Disturbances

- A Primary Set of 10 Digitally-Saved Disturbances Will Be Available for All Testbed Users

X_n, Y_n, θ_n = X, Y Displacements and Rotation About Z Axis of C.G. of Bay n

Figure 18. Strawman Controls Experiment

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
January 1992

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Mini-Mast CSI Testbed User's Guide

5. FUNDING NUMBERS
WU 590-14-61-01

6. AUTHOR(S)
Sharon E. Tanner, Richard S. Pappa, Jeffrey L. Sulla, Kenny B. Elliott, Robert Miserentino, James P. Bailey, Paul A. Cooper, Boyd L. Williams, Jr., and Anne M. Bruner

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23665-5225

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronuatics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-102630

11. SUPPLEMENTARY NOTES
Tanner, Pappa, Elliott, Miserentino, Cooper: Langley Research Center, Hampton, VA; Sulla, Bailey, Williams, and Bruner: Lockheed Engineering & Sciences Co., Hampton, VA.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited

Subject Category 39

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
The Mini-Mast testbed is a 20-meter-long generic truss highly representative of future deployable trusses for space applications. It is fully instrumented for system identification and active vibrations control experiments and is used as the first ground testbed at NASA Langley Research Center for the Controls-Structures Interaction (CSI) program. The facility has actuators and feedback sensors linked via fiber optic cables to the Advanced Real-Time Simulation (ARTS) system, where user-defined control laws are incorporated into generic controls software. The object of the facility is to conduct comprehensive active-vibration-control experiments on a dynamically realistic large space structure. A primary goal is to understand the practical effects of simplifying theoretical assumptions. This User's Guide describes the hardware and its primary components, the dynamic characteristics of the test article, the control law implementation process, and the necessary safeguards employed to protect the test article. Suggestions for a strawman controls experiment are also included.

14. SUBJECT TERMS
Experimental; Testbed; CSI; Truss; Test; Controls; Large Space Structures; Mini-Mast

15. NUMBER OF PAGES
45

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT